# Neutrino electromagnetic properties and new bounds on neutrino magnetic moments

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**Abstract.** We give a brief outline of possible neutrino electromagnetic characteristics, which can indicate new physics beyond the Standard Model. Special emphasis is put on recent theoretical development in searches for neutrino magnetic moments.

## 1. Introduction

In particle physics, the neutrino plays a remarkable role of a "tiny" particle. Indeed, the scale of neutrino mass $m_\nu$ is much lower than that of the charged fermions ($m_{\nu_f} \ll m_f$, $f = e, \mu, \tau$). Interaction of neutrinos with matter is extremely weak as compared to that in the case of other known elementary fermions, and it can be mediated via the weak or electromagnetic channel. In this context, neutrino electromagnetic properties are of particular interest, for they open a door to "new physics" beyond the Standard Model (SM) [1]. In spite of appreciable efforts in searches for electromagnetic properties of neutrino, up to now there is no experimental evidence favoring their nonvanishing electromagnetic characteristics. However, the recent development of our knowledge of neutrino mixing and oscillations, supported by the discovery of flavor conversions of neutrinos from different sources, makes quite plausible the assumption that neutrinos have "nonzero" electromagnetic properties. The latter include, in particular, the electric charge, the charge radius, the anapole moment, and the dipole electric and magnetic moments.

The neutrino magnetic moments (NMM) expected in the SM are very small and proportional to the neutrino masses[1] [2]:

$$\mu_\nu \approx 3 \times 10^{-19} \mu_B \left( \frac{m_\nu}{1\,\mathrm{eV}} \right), \tag{1}$$

with $\mu_B = e/2m$ being the electron Bohr magneton, and $m$ is the electron mass. Thus any larger value of $\mu_\nu$ can arise only from physics beyond the SM (a recent review of this subject can be found in [3]). Current direct experimental searches [4, 5, 6, 7] for a magnetic moment

[1] The units $\hbar = c = 1$ are used throughout unless otherwise stated.

of the electron (anti)neutrinos from reactors have lowered the upper limit on $\mu_\nu$ down to $\mu_\nu < 3.2 \times 10^{-11}\,\mu_B$ [6, 7]. These ultra low background experiments use germanium crystal detectors exposed to the neutrino flux from a reactor and measure the energy $T$ deposited by the neutrino scattering in the detector. The sensitivity of such a search to NMM crucially depends on lowering the threshold for the energy transfer $T$, due to the enhancement of the magnetic scattering relative to the standard electroweak one at low $T$.

The paper is organized as follows. In section 2, we discuss electromagnetic characteristics that one may expect in the cases of Dirac and Majorana neutrinos. Specific theoretical aspects of searches for NMM are considered in section 3. Section 4 summarizes this work.

## 2. Electromagnetic properties of neutrino

In general the matrix element of the electromagnetic current $J_\mu^{\rm EM}$ can be considered between different neutrino initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses, $p^2 = m_i^2$ and $p'^2 = m_j^2$:

$$\langle \psi_j(p')|J_\mu^{\rm EM}|\psi_i(p)\rangle = \bar{u}_j(p')\Lambda_\mu(q)u_i(p). \tag{2}$$

In the most general case consistent with Lorentz and electromagnetic gauge invariance, the vertex function is defined as (see Ref. [3] and references therein)

$$\Lambda_\mu(q) = [f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5](q^2\gamma_\mu - \gamma_\mu \not{q}) + f_M(q^2)_{ij} i\sigma_{\mu\nu}q^\nu + f_E(q^2)_{ij} i\sigma_{\mu\nu}q^\nu\gamma_5, \tag{3}$$

where $f_Q(q^2)$, $f_A(q^2)$, $f_M(q^2)$, and $f_E(q^2)$ are respectively the charge, anapole, dipole magnetic, and dipole electric neutrino form factors, which are matrices in the space of neutrino mass eigenstates [8].

Let us briefly discuss the diagonal case $i = j$. The hermiticity of the electromagnetic current and the assumption of its invariance under discrete symmetries transformations put certain constraints on the neutrino form factors, which are in general different for the Dirac and Majorana cases. In the case of Dirac neutrinos, the assumption of CP invariance combined with the hermiticity of the electromagnetic current $J_\mu^{\rm EM}$ implies that the electric dipole form factor vanishes, $f_E = 0$. At zero momentum transfer only $f_Q(0)$ and $f_M(0)$, which are called the electric charge and the magnetic moment, respectively, contribute to the Hamiltonian $H_{\rm int} \sim J_\mu^{\rm EM} A^\mu$, which describes the neutrino interaction with the external electromagnetic field $A^\mu$. Hermiticity also implies that $f_Q$, $f_A$, and $f_M$ are real. In contrast, in the case of Majorana neutrinos, regardless of whether CP invariance is violated or not, the charge, dipole magnetic and electric moments vanish, $f_Q = f_M = f_E = 0$, so that only the anapole moment can be non-vanishing among the electromagnetic moments. Note that it is possible to prove [9, 10, 11] that the existence of a non-vanishing magnetic moment for a Majorana neutrino would bring about a clear evidence for CPT violation.

In the off-diagonal case $i \neq j$ the hermiticity by itself does not imply restrictions on the form factors of Dirac neutrinos. It is possible to show [11] that if the assumption of CP invariance is added, the form factors $f_Q$, $f_M$, $f_E$, and $f_A$ should have the same complex phase. For the Majorana neutrino, if CP invariance holds, there could be either a transition magnetic or a transition electric moment. Finally, as in the diagonal case, the anapole form factor of a Majorana neutrino can be nonzero.

## 3. Searches for neutrino magnetic moments

The neutrino dipole magnetic and electric form factors (and the corresponding magnetic and electric dipole moments) are theoretically the most well studied among the form factors. They also attract a notable attention from experimentalists, although the NMM value (1) predicted in the SM is many orders of magnitude smaller than the present experimental

limits achievable in terrestrial experiments. The most sensitive and established method for the experimental investigation of the NMM is provided by direct laboratory measurements of electron (anti)neutrino-electron scattering at low energies in solar, accelerator, and reactor experiments. A detailed description of various experiments can be found in [5, 12].

The cross section for electron (anti)neutrino scattering on a free electron can be written [13] (see also [5, 12]) as a sum of the SM and NMM contributions,

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\rm SM}}{dT} + \frac{d\sigma_{(\mu)}}{dT}, \tag{4}$$

where $E_\nu$ is the incident neutrino energy and $T$ is the energy transfer. The SM contribution is constant in $T$ at $E_\nu \gg T$:

$$\frac{d\sigma_{\rm SM}}{dT} = \frac{G_F^2 m}{2\pi}\left(1 + 4\sin^2\theta_W + 8\sin^4\theta_W\right)\left[1 + O\left(\frac{T}{E_\nu}\right)\right] \approx 10^{-47}{\rm cm}^2/{\rm keV}. \tag{5}$$

In contrast, the NMM contribution

$$\frac{d\sigma_{(\mu)}}{dT} = 4\pi\alpha\mu_\nu^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right) = \pi\frac{\alpha^2}{m^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2\left(\frac{1}{T} - \frac{1}{E_\nu}\right) \tag{6}$$

exhibits a $1/T$ enhancement at low energy transfer. Note that the NMM contribution to the cross section changes the helicity of the neutrino, contrary to the SM contribution and to the possible contribution from the neutrino charge radius. Therefore, for relativistic neutrino energies the interference between $d\sigma_{\rm SM}/dT$ and $d\sigma_{(\mu)}/dT$ is a negligible effect in the total cross section (4).

The current experiments with reactor (anti)neutrinos have reached threshold values of $T$ as low as few keV and are likely to further improve the sensitivity to low energy deposition in the detector. At low energies however one can expect a modification of the free-electron formulas (5) and (6) due to the binding of electrons in the germanium atoms, where e.g. the energy of the $K_\alpha$ line, 9.89 keV, indicates that at least some of the atomic binding energies are comparable to the already relevant to the experiment values of $T$. In the case $E_\nu \gg T$, which is relevant to the experiments with reactor (anti)neutrinos, it can be shown [14, 15, 16] that the SM and NMM contributions to the neutrino scattering on atomic electrons are

$$\frac{d\sigma_{\rm SM}}{dT} = \left(\frac{d\sigma_{\rm SM}}{dT}\right)_{\rm FE}\frac{I_1(T)}{2m}, \qquad I_1(T) = \int_0^\infty S(T, q^2)dq^2, \tag{7}$$

$$\frac{d\sigma_{(\mu)}}{dT} = \left(\frac{d\sigma_{(\mu)}}{dT}\right)_{\rm FE} T I_2(T), \qquad I_2(T) = \int_0^\infty S(T, q^2)\frac{dq^2}{q^2}, \tag{8}$$

where $(d\sigma_{\rm SM}/dT)_{\rm FE}$ and $(d\sigma_{(\mu)}/dT)_{\rm FE}$ are the free-electron results given by (5) and (6), respectively. A key quantity that determines cross sections (7) and (8) is the so-called dynamical structure factor $S(T, q^2)$, which is a function of the energy and momentum transfer values, $T$ and $q = |\mathbf{q}|$. For a free electron, one has in a nonrelativistic limit $S(T, q^2) = \delta(T - q^2/2m)$, which upon substitution in (7) and (8) immediately yields the free-electron formulas (5) and (6).

Recently it was claimed [17] that the atomic binding effects must result in a significant enhancement of the NMM contribution. However, that early claim was later disproved [14, 18, 19], thus also disproving the upper bound on the $\mu_\nu$ value, $\mu_\nu < 1.3 \times 10^{-11}\mu_B$, obtained in [17]. It was demonstrated [15, 16] by means of analytical and numerical calculations that the atomic binding effects are adequately described by the so-called stepping approximation introduced in [20] from interpretation of numerical data. According to the stepping approach, the SM and NMM contributions are simply given by

$$\frac{d\sigma_{\rm SM}}{dT} = \left(\frac{d\sigma_{\rm SM}}{dT}\right)_{\rm FE}\sum_i n_i\theta(T - E_i), \qquad \frac{d\sigma_{(\mu)}}{dT} = \left(\frac{d\sigma_{(\mu)}}{dT}\right)_{\rm FE}\sum_i n_i\theta(T - E_i), \tag{9}$$

where the $i$ sum runs over all occupied atomic sublevels, with $n_i$ and $E_i$ being their occupations and binding energies. The following important conclusions can be drawn from the stepping approximation (9). Firstly, the atomic effects reduce the SM and NMM contributions compared to their free-electron values. Secondly, the ratio between the SM and NMM contributions is not affected by the atomic binding effects.

## 4. Conclusion

The above theoretical findings strongly support the upper limit $\mu_\nu < 3.2 \times 10^{-11}\mu_B$ recently reported by the GEMMA collaboration [6, 7]. This bound obtained in terrestrial experiments with reactor (anti)neutrinos is only by an order of magnitude weaker than the most stringent astrophysical constraint $\mu_\nu < 3 \times 10^{-12}\mu_B$ [21]. A general and model-independent upper bound on the Dirac NMM, that can be generated by an effective theory beyond the SM, is $\mu_\nu \leq 10^{-14}\mu_B$ [22] (the limit in the Majorana case is much weaker). Thus, the searches for NMM are close to the territory where new physics can reveal itself.


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